GOOD PRACTICE GUIDE 269

Efficiency improvements to existing distillation equipment

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GOOD PRACTICE GUIDE 269

EFFICIENCY IMPROVEMENTS TO EXISTING DISTILLATION EQUIPMENT

This Guide is No. 269 in the Good Practice Guide series and it provides advice on practical ways of improving energy efficiency in distillation operations. The Guide reviews distillation in general, and provides guidance on how to determine current energy performance and the scope for improvement. It covers ways of improving energy efficiency ranging from basic improvement strategies and energy-saving revamps, through to advanced techniques suitable for comprehensive revamps and new equipment. Case studies are also included which show the savings that can be achieved in practice.

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FOREWORD

This Guide is part of a series produced under the Energy Efficiency Best Practice Programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded strips for easy reference:

— *Energy Consumption Guides:* (blue) energy consumption data to enable users to establish their relative energy efficiency performance;

— *Good Practice Guides:* (red) and *Case Studies:* (mustard) independent information on proven energy-saving measures and techniques and what they are achieving;

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1. INTRODUCTION

Distillation is the most widely used of the fluid separation processes and is normally the first process to be considered. It has been used for centuries, but it is only during the last hundred years that significant equipment development has occurred.

Fig 1 Typical distillation equipment

Distillation columns perform about 95% of all fluid separations in the chemical industries, and their use accounts for an estimated 3% of total world energy consumption. Distillation processes in the UK process industries alone are estimated to consume energy worth around £340 million. There is potential for significant energy and financial savings in many distillation operations. It is estimated that 10 - 15% excess energy is used in a wide range of distillation applications.

Ways of improving energy efficiency in existing distillation equipment range from simple low-cost operational improvements to large-scale revamps. While large-scale revamps to reduce energy consumption alone are not normally justifiable on economic grounds, if a revamp is planned for other reasons, separation energy should be considered.

All distillation columns are inefficient: this Guide will help you determine to what extent the efficiency of your distillation equipment can be improved.

Energy transfer occurs in distillation:

- to preheat the feedstock;
- in the condenser (removed from column);
- in the reboiler;
- through pressure drop.

Losses can occur for many reasons, such as:

- poor insulation;
- excessive reboil/reflux;
- generation of excessively pure products;
- poor control strategy;
- fouling;
- insufficient separation stages resulting in higher reflux rates;
- non-optimum feed conditions.

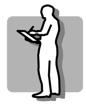
This Good Practice Guide provides simple guidance for management on the operation, design and maintenance of distillation equipment to improve overall efficiency. Energy-saving opportunities that may occur in routine operation are identified, as well as those to be found during operations to reduce bottlenecks or during equipment revamps.

Section 2 covers use of distillation, describing basic distillation, energy use and reasons for losses, and principal distillation column arrangements.

Section 3 covers the first steps needed to improve the efficiency of your distillation operation, describing how to compare current operation with the original design specifications.

Sections 4, 5 and 6 provide an overview of how efficiency can be improved through low-cost operational changes, revamps of existing equipment and application of advanced technology to new equipment, respectively. Opportunities are categorised as:

 design;

 operation;

 monitoring;

 maintenance.

Examples of projects in industry are included, showing the scope for savings. In one case, installing an on-line product analyser at a cost of £20,000 cut energy use by £80,000/year by reducing the reboiler duty.

Section 7 provides a checklist of the main energy-saving opportunities in distillation operations.

Section 8 presents a series of case studies which demonstrate how various improvement schemes have produced substantial savings for little outlay.

Section 9 contains a bibliography.

2. USE OF DISTILLATION

2.1 Basic Distillation

Separation of homogeneous fluid mixtures requires the creation or addition of another phase. The most commonly used separation process is distillation, which uses the different vapour-liquid equilibrium concentrations of the components in the mixture to achieve separation.

Distillation has three main advantages over other methods of separation:

- it can handle a wide range of throughput;
- it can handle a wide range of feed concentrations;
- it can produce a high purity product.

In a distillation column, mass transfer is achieved by contacting vapour and liquid phases. Countercurrent flow through a number of stages increases the concentration of lighter components (with a low boiling point) towards the top of the column, and heavier components (with a high boiling point) towards the bottom. Generally, the staged contacting device uses trays or packing.

Most distillation columns are equipped with a reboiler at the base to provide the necessary heat to vaporise the liquid. Heat can also be provided by side reboilers, and can be removed in side condensers or pumparounds.

Overhead vapours from the top of the column are condensed, and part of this is withdrawn as product, while the rest is returned to the top of the column as reflux. The amount of external heating and cooling is related to the reflux ratio, i.e. the ratio of reflux returned per unit quantity of condensate removed as product. The higher the reflux ratio, the greater the energy use. Difficult separations (defined by the vapour-liquid equilibrium characteristics) require high reflux ratios and therefore use more energy than easy separations. Generally, a large number of stages reduces the reflux ratio, and hence the energy requirement, but increases capital costs.

2.2 Energy Use in Distillation

2.2.1 *Condenser and Reboiler Duties*

In the majority of distillation columns, the largest energy users are the reboiler and the condenser. Column design takes into account a number of factors which affect energy use in these units.

- *Product properties*

  Column conditions are primarily dictated by the properties of the materials being distilled. All components must be above their melting points and below their critical points. Conditions are selected to avoid polymerisation, decomposition, foaming or reaction (unless desired). The temperatures in the condenser and the reboiler are the most important parameters.

- *Reboiler and condenser temperatures*

  Temperatures are influenced by column pressure. Generally, but not always, lower pressures result in easier separation and hence lower absolute energy requirements. The lowest operating costs, however, are usually achieved by using the cheapest combination of hot and cold utilities. Distillation costs increase significantly if refrigeration is used. Therefore, column pressure is often selected to allow use of the cheapest available hot utility (e.g. low pressure steam) that will still allow the use of cooling water or air in the condenser. Where temperatures are high enough, it is sometimes possible to generate steam in the overhead condenser for use elsewhere (e.g. to preheat feed), reducing overall energy requirements.

- *Reflux ratio*

  Lower reflux ratios result in lower energy requirements, but a greater number of stages. Column design is therefore a trade-off between operating and capital costs.

2.2.2 *Feed and Product Conditions*

To minimise the energy required for separation, column liquid feed should be at its boiling point as a saturated liquid or be a saturated vapour, and needs to be fed into the column at the point most closely matching its temperature and composition. To achieve this, many operational columns have several feed trays, allowing operating costs to be minimised by changing feed trays for different feedstocks.

Feed temperature affects both energy requirement and column throughput. For example, to raise a sub-cooled liquid feed to its bubble point, the reboiler needs to produce extra vapour, increasing energy use. If the feed can be raised to its bubble point using a cheaper utility or recovered heat *before entering the column*, operating costs can be reduced. Cold feed increases both the liquid and vapour flows in the column below the feed, which can lead to flooding and reduced throughput.

Distillation energy use is also affected by product conditions. If an overhead product can be used in the vapour phase (e.g. in a reactor or as feed to a further column), the column condenser need only provide sufficient liquid for reflux. If the downstream process is a distillation column, the reboiler duty in this column should also be reduced. If a refrigerant is required in the condenser, use of a partial condenser can reduce distillation costs significantly.

To minimise the energy requirements of a multi-component split:

- remove side-stream product above the feed as a liquid, i.e. the lighter impurities remain in the vapour phase;
- remove side-stream product below the feed in the vapour phase, i.e. the heavy impurities remain in the liquid in the column.

2.2.3 *Pressure Drop*

Pressure drop is particularly important for distillation under vacuum. A small absolute pressure drop in these circumstances can equate to a large relative difference in pressure between the top and the bottom of the column. Since low pressures generally mean better relative volatility, minimising pressure drop also minimises reflux and reboil requirements. Bottom product temperature is also lowered, reducing product degradation.

2.3 Principal Distillation Column Arrangements

The principal distillation column arrangements are shown in Fig 2. Distillation column variants include use of side condensers and reboilers, pumparounds and side strippers.

Liquid-vapour contact in distillation columns can be achieved using trays, structured packings or random packings (Table 1).

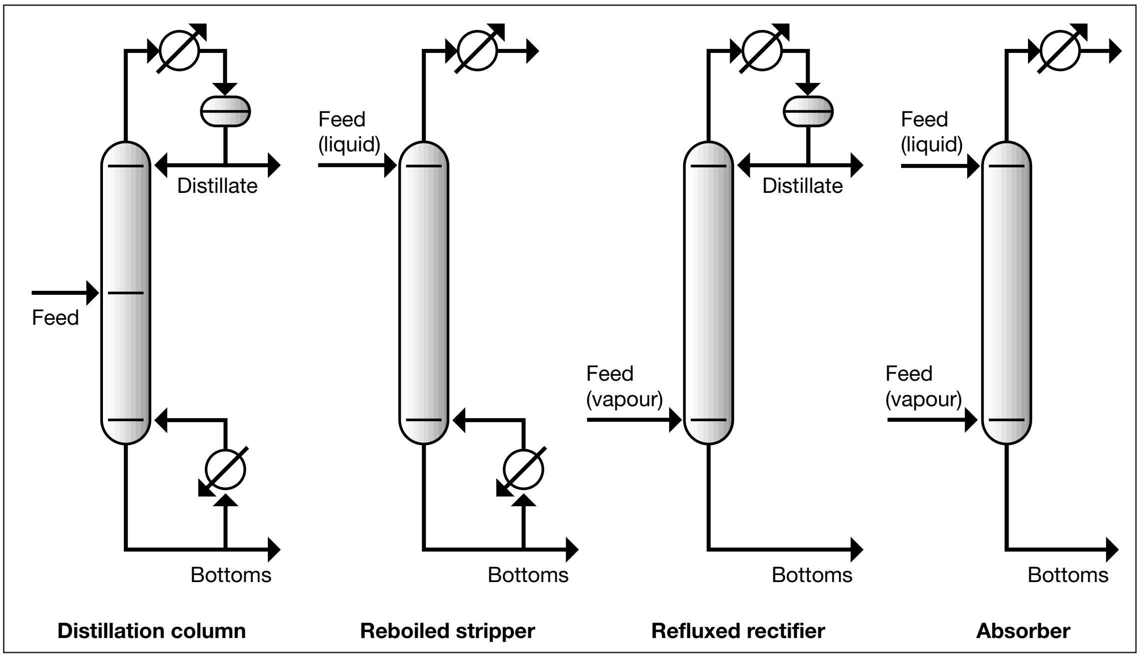


Fig 2 Principal distillation column arrangements

Table 1 Preferred column types for distillation uses

Packed columns are favoured for:	**Tray columns** are favoured for:
• Vacuum distillation because of the inherent low pressure drop.	• High liquid rates because they can be accommodated using multipass trays.
• Corrosive systems because of the wide range of materials available.	• High liquid hold-up because they enable chemical reactions/absorption within column.
• Low liquid hold-up because of the suitability for hazardous materials.	• Small quantities of solids because the design is suited to high vapour and liquid velocities.
	• Turndown ratio because feed rate of column can be changed without causing problems.

2.3.1 *Packings*

Packings are divided into random and structured types. Random packings, such as Raschig rings, Pall rings and saddles, are individual pieces of packing of a particular geometrical shape which are packed into the column, forming a random structure. Structured packings are layers of wire mesh or corrugated sheets arranged in sections, which are stacked in the column.

The method of liquid-vapour contact is the same for both packing types. The liquid is distributed over the packing, forming a thin layer, and then runs down the column. The vapour passes up the column through the spaces in the packing structure.

The separation efficiency of a packed column depends on the liquid forming a uniform layer over the packing surface. The liquid must be distributed such that uniform wetting is achieved in as short a height of packing as possible. Liquid flow is not, however, perfectly even, particularly in random packings. As a result, liquid can reach the column walls where it runs down with reduced vapour contact, or liquid channels can form in the packing which also reduce efficiency. Liquid collectors and distributors along the column length will improve efficiency.

Height Equivalent of a Theoretical Plate (HETP) is often used to describe the separation efficiency of a packing. HETP is the height of packing required to perform the same separation as a theoretical tray. In general, packings with a higher surface area per unit volume have a lower HETP and therefore a higher efficiency.

Fig 3 Structured packing

As with tray columns, packed columns have performance limits. At high liquid rates, the spaces within the packing fill with liquid, reducing efficiency, until ultimately the column gets completely flooded. At high vapour rates, liquid can be entrained and accumulate within the column bed.

2.3.2 *Trays*

In tray columns, liquid flows down the column, passing across trays and down downcomer channels. A weir on each tray retains a head of liquid and provides a liquid seal which prevents vapour passing up the downcomers. In normal operation, vapour passes up the column through holes in the trays, bubbling through the liquid.

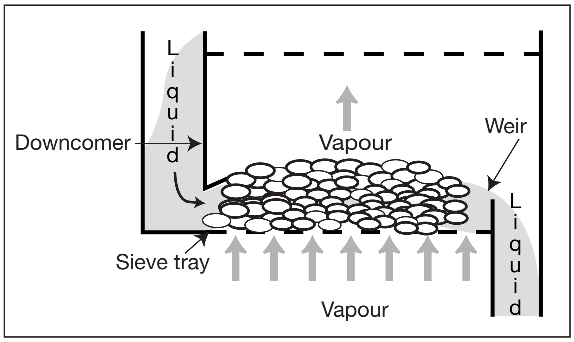


Fig 4 Liquid-vapour contact in a tray column

There are three main types of tray.

- *Sieve trays*

  These consist of a plate with a number of holes. Vapour rising up the column supports liquid on the trays. At low throughput where vapour flow is insufficient, liquid weeps through the holes. This reduces liquid-vapour contact and hence column performance. At extremely low vapour flows, the liquid is dumped to the bottom of the column.

- *Valve trays*

  These trays incorporate a valve mechanism on each hole and achieve a better turndown ratio before weeping occurs. However, they still dump the liquid inventory on shutdown.

- *Bubble caps*

  Bubble caps form a liquid seal on the trays allowing turndown to zero without dumping the liquid inventory, but have a relatively high pressure drop.

Other forms of tray are used in particular applications, e.g. dual flow trays for fluids containing small amounts of solids.

Tray performance is dependent on vapour and liquid flowrates in the column and internals dimensions. Excessive liquid accumulation, or flooding, occurs when performance limits are exceeded, for example:

- At low liquid and high vapour rates, the bulk of the liquid is entrained as droplets in the vapour and carried to the stage above, where it accumulates.
- At high liquid and vapour rates in columns with small tray spacing, the froth height on trays increases such that liquid from the froth becomes entrained into the tray above, where it accumulates.
- At high liquid rates, liquid in the downcomer can backup due to increased tray pressure drop, liquid height on the tray and frictional losses in the downcomer. The result is that liquid cannot be transported to the tray below and it accumulates.

Fig 5 Looking up at a sieve tray during column fabrication

3. TAKE A FRESH LOOK AT YOUR DISTILLATION COLUMN

A careful review of column operation often reveals inadequacies in performance that can readily be corrected. A recent survey[1] of 300 reported column malfunctions revealed that 20% resulted from instrument and control problems. Other common causes included start-up/shutdown difficulties, and malfunctioning column internals, reboilers and condensers. With tray columns, most cases of reduced capacity or flooding were found to result from downcomer flooding.

Fig 6 Distillation column

This Section lists what data you need to assess current column performance and shows how to compare this with the original design specifications. This exercise will reveal the extent of column inefficiencies and should enable you to pinpoint the areas likely to produce the greatest energy savings.

Additional detailed and comprehensive guidance on performance testing and evaluation is given in Chapter 14 of *Distillation Operation* (see Section 9, Bibliography).

3.1 Current Operation

Before starting on any projects to improve column performance, you need to know your current position. The first step involves a data-gathering exercise. Data collection must be thorough and systematic. The following approach usually produces sufficient data.

- Ask key staff for their opinions and ideas.
- Listen to observations about operational procedures and problems.
- Measure key distillation parameters:
  - feed and product rates;
  - feed and product compositions;
  - temperatures - feed, reboiler, condenser and, where available, column profile;
  - pressures - condenser, reboiler and, where possible, column profile;
  - reboiler duty - steam flow;
  - condenser duty;
  - reflux rate.
- Study historical records for any patterns and relationships.
- Validate data.
- Analyse data.

In addition to column operating parameters, information about the column geometry is important for assessing operating problems caused by the physical limits of the column:

- type(s) of internals;
- number of stages or height of packing;
- geometry of internals;
- design of feed distribution.

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[1] Kunesh J G, Kister H Z, Lockett M J and Fair J R, *Distillation: Still Towering Over Other Options*, Chemical Engineering Progress, 91(10), pages 43 - 54 (1995).

For columns with serious operational problems, non-invasive, external investigation is possible using radioactive techniques. Quantitative analysis of gamma scans has proved extremely useful. New techniques such as computer-aided tomography (CAT) can detect hydraulic problems in an operating column, such as abnormal spray heights, tray flooding and downcomer flooding, and any damage to column internals. To determine the problem, columns are often scanned under unstable conditions, for example when running close to flooding or during process cycling.

3.2 Compare Current Performance with Design Specification

Once you have determined current performance, it is necessary to compare this with the original design specification, obtained from design data sheets or a process flow diagram (PFD). An initial pass at the data may reveal reasons for the apparent poor performance. For example, a significantly different feed composition can lead to completely different column performance.

Computer simulation of column operation is a valuable tool for determining the causes of deviation from desired operation. Where a simulation of the expected column operation is available (based on reliable thermodynamic property data), this too should be compared with actual operating data. In addition, simulation can be used for evaluating potential modifications.

3.3 Reasons for Poor Column Performance

There are several possible reasons for any deviation from design performance and a thorough performance evaluation may be needed to determine the precise cause(s).

Example of deviation from design performance and possible causes

- A high reboiler temperature indicates possible reboiler fouling or a change in bottom product composition caused by a higher concentration of heavy components (resulting from increased recovery or the formation of heavies in the column).
- A large pressure drop indicates possible column flooding.
- Distribution problems in the column may result from different feed conditions. For example, if the column was designed for a sub-cooled liquid feed, but subsequent changes have resulted in a two-phase or vapour feed, the distributor may not be suited to the new conditions.
- Limited condenser duty may result from the accumulation of trace non-condensables contained in the feed as a result of inadequate purging.
- Large reboiler and condenser duties may be used by operators to ensure a ‘safe operating’ position, resulting in above-design purities and significant additional energy consumption.

Poor column performance can also result from:

- poor control
- poor distributor performance in packed columns;
- presence of solids in the column;
- plugging and fouling of packing and trays;
- trays being out of level;
- poor vapour distribution on tray and vapour cross-flow;
- poor understanding of how to operate the column in line with business objectives.

4. BASIC IMPROVEMENT STRATEGIES

In many distillation operations, simple low-cost operational improvements can significantly improve energy efficiency and result in operation close to design specification.

4.1 Where to Start?

Almost 60% of reported malfunctions in distillation[2] are caused by operational difficulties, troublesome column internals, instrument and control problems and installation mishaps. Malfunctioning reboilers and condensers, and start-up/shutdown difficulties account for just under half of the remaining problems. An understanding of these issues provides one starting point for an energy efficiency study.

4.2 Initial Checklist of Key Energy-saving Areas

When looking to improve the energy efficiency of your distillation operations, consider the following areas first. Simple operational changes in these areas are likely to yield significant energy savings.

- ☐ Is product specification correct? Excessive product purity requires more energy.
- ☐ Is feed condition adequately specified and controlled? Poorly specified feed conditions can result in poor column performance.
- ☐ Is optimum reflux determined, and is the column controlled at the optimum value? Over refluxing/reboiling wastes energy.
- ☐ Is the reboiler control adequate? Avoid excess steam consumption.
- ☐ Is column pressure correct? Higher pressures result in more difficult separations.
- ☐ Is insulation of column, reboiler, condenser and pipework adequate and in good condition? Heat losses increase the load on reboilers and condensers.
- ☐ Are steam traps properly maintained? Poorly maintained traps can leak and pass steam.
- ☐ Is condensate recovery in place?

4.3 Low-cost Operational Improvements

4.3.1 *Product Specification*

Product specification is the key factor in the design and operation of any distillation column. Most columns are carefully designed and optimised, but actual operation may be far removed from the optimal condition. In an existing column, specification is normally controlled by the reflux ratio (energy input) and the product flows (overall mass balance). Any deviations in specification will have a direct impact on the column energy requirements. Savings associated with product can arise by:

- increasing the price for higher purity product;
- shifting separation duty to more efficient downstream equipment;
- avoiding excessive purification due to over-refluxing;
- avoiding any mismatch of products for multiple downstream users.

In many cases, distillation operations produce a product with a higher purity than that originally specified by the customer. However, if a higher price can be charged for the higher purity product, the increased revenue often more than covers the cost of the increased energy use and column operation remains unchanged. Check what energy savings would result from matching product purity to actual customer needs, to determine whether operational changes would be cost-effective.

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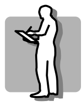
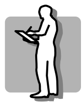
[2] Kister H Z, *Distillation and Absorption*, Institution of Chemical Engineers Symposium Series No 142 (1997).



Where products are further processed, even after they leave site, it may be possible to shift some of the separation duty to more efficient downstream equipment. For example, a column with a limited number of stages purifying a stream to 98% may not be as energy efficient as a downstream column with a larger number of stages purifying to 99.9%. Reducing the separation in the first column to 95% may result in an overall energy saving.



Reducing over-refluxing caused by conservative operational safety margins can give significant savings.

Instrumentation enables product specification to be met with reduced energy requirement

A debutaniser making a bottom product with not more than 1% isobutane was controlled by the flow of steam to the reboiler. Varying composition meant that temperature could not be correlated with isobutane concentration. Since the operators had no quick way of checking isobutane concentration, maximum reflux and reboil rate were used to ensure that product always complied with specification. A sample of the bottom product was sent to the laboratory for analysis each day, and if the result showed less than 1% isobutane, it was ignored. More importantly, a 0.1% isobutane concentration did not result in the operators cutting reflux to save steam.

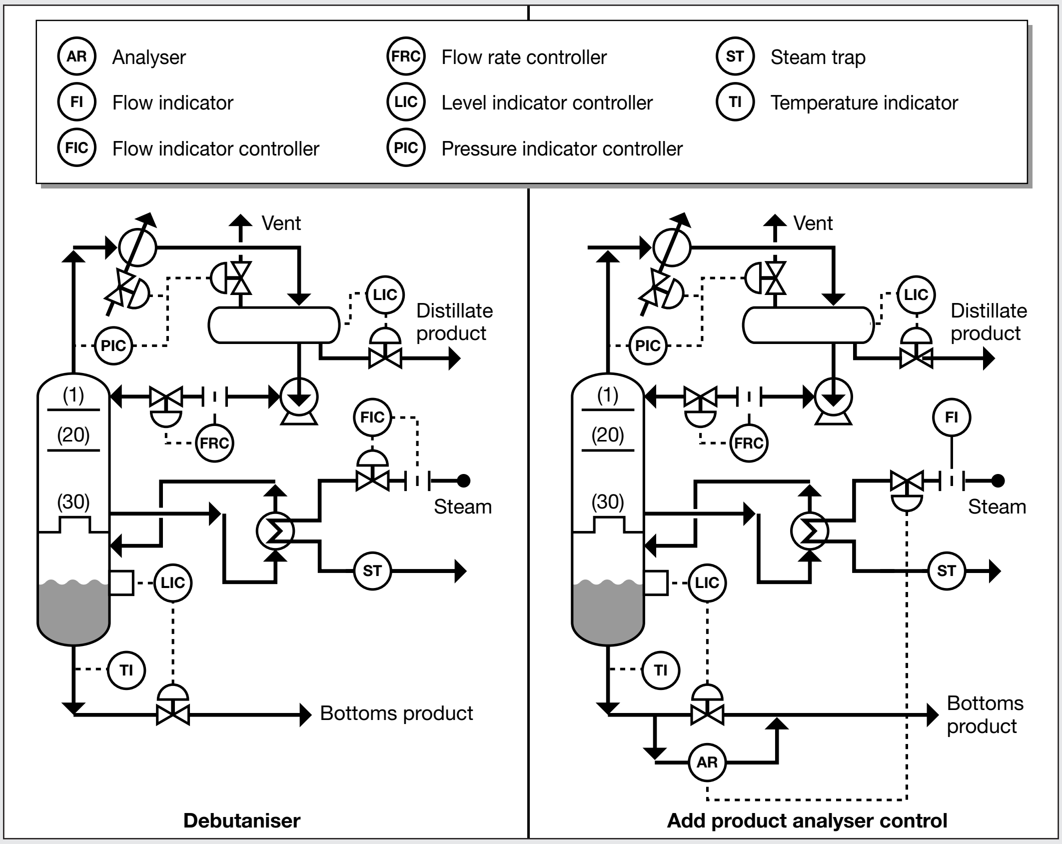


Fig 7a Original debutaniser control

Fig 7b Modified debutaniser control

To encourage operators to save reboiler steam, an on-line chromatograph was installed at a cost of £20,000. A reasonably stable column operation was obtained and the variation in isobutane concentration (0.8% to 1.2%) was evened out in the product tank. Energy savings of £80,000/year were achieved and product ‘giveaway’ was minimised, as the downgrade of higher value components was reduced.

It should be mentioned that it may be possible to avoid the use of an analyser using inferential models and model-based control. In any event, it is good practice to use inferential methods even when an analyser is available as analyser reliability is often low and they suffer from high deadtime.

With multiple downstream users, the usual practice is to produce the total product to the highest specification. It may be possible to produce a side stream from the column which satisfies some of the downstream users, reducing overall separation energy and removing bottlenecks in the column.

4.3.2 *Feed Conditioning*

Feed conditioning is one of the commonest methods of reducing the energy required by a distillation column. Heating a feed can reduce the load on a reboiler, but the savings potential depends on the split between overhead and bottom product. For example, with an 80% overhead product, 20% bottom product split, a vapour feed would produce the greatest savings, whereas with a 20% overhead product, 80% bottom product split, a vapour feed would provide negligible savings. Column profiles can help identify the potential benefits of feed pre-treatment (see Section 5.2).

Distillation column feed can come from many types of processing equipment, such as another distillation column, a heat exchanger or a reactor, and there is often scope to modify feed condition. For example, if the stream comes from the overhead of a preceding column it can be taken either as all vapour (provided sufficient pressure differential exists) or as all liquid. Heat exchangers can be modified or added to heat or cool the feed. Steam can be used to heat the feed, but must be at a lower pressure (and, therefore, at a lower cost), than that being used in the reboiler to produce savings. Heat recovery from process streams is the ideal low-cost way to heat or cool the feed.

Feed conditioning in a column where 80% of the feed is recovered as the overhead product can halve reboiler duty and cut utility costs by 40%

If feed condition is shifted from saturated liquid to saturated vapour, the condenser duty changes only moderately, while the reboiler duty is more than halved. For a column condensed with cooling water and reboiled with low pressure (LP) steam, the utility costs are 40% lower for the all-vapour feed. As capital costs change very little over the range of feed condition, an all-vapour feed will result in the most cost-effective performance. Where the column feed comes from the overhead of a preceding column, it should be taken as all vapour if possible.

If a column has a refrigeration condenser, the high cost of refrigeration compared with cooling water greatly reduces the justification for feed heating. In these circumstances, increasing condenser duty significantly may increase operating costs to such an extent that it may prove economical to condense the feed in a cooling water exchanger.

4.3.3 *Reflux Optimisation*

Reflux optimisation during distillation column design is a trade-off between the capital cost of the stages and the operating cost for the utilities, providing the reflux and associated reboil. Reducing reflux saves cooling duty in the condenser and heating duty in the reboiler, but also reduces product purities in an existing column with a fixed number of stages. Installing more stages into an existing column is possible, but is considered as a design change.

In an existing distillation column the optimisation of reflux is determined economically by trading off yield, purity and energy. This can best be illustrated by considering two sets of economies:

1. *Where both products have similar values and the cost of energy is relatively high.* The column should be operated with all products at maximum impurity levels as the cost of increasing energy use outweighs additional product yield benefits. High purity products are often controlled in this way.
2. *Where there is one very valuable product and one of little or no value and energy is cheap.* The column is operated at maximum fractionation. The valuable product is controlled at maximum recovery and impurity which normally means that the column is operated at some hardware limit (ie, maximum approach to flood).

There are scenarios which lie in between these two cases where the two products have different values and energy has a reasonable cost. The optimal energy input is the point where the most valuable product is controlled at maximum impurity and any further increase in energy outweighs the additional product yield benefit. The less expensive product will be over-purified in this case.

4.3.4 *Sub-cooled Reflux*

Sub-cooled reflux is usually caused by over-capacity in the condenser, resulting in degradation of the temperature profile within the condenser. Depending on the condenser utility, this can lead to a higher use of cooling water or a reduction in steam generation. Avoiding sub-cooling can produce energy savings in cooling water pumping and/or air cooler fans.

Improved column control avoids sub-cooled reflux

A depropaniser was pressure-controlled by an oversized ‘flooded condenser’. Much of the condenser’s surface area was wasted, since most of the tubes were normally submerged. To use the excess surface area and save cooling water, the cooling water inlet valve was partially closed. On occasion, operators needed to increase cooling water flow and, after a few such incidents, they decided to leave the cooling water valve open.

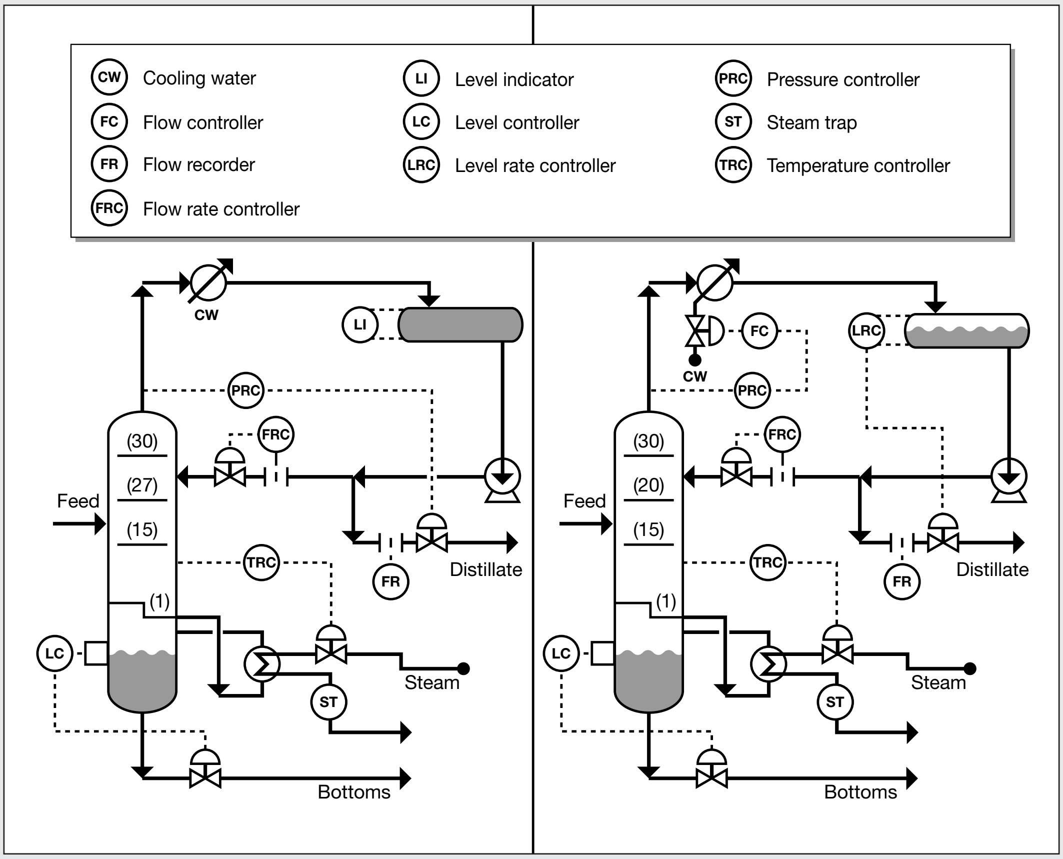


Fig 8a Distillation using flooded condenser

Fig 8b Avoiding overhead condenser flooding

Changes to column control, primarily a cooling water valve controlled by the column pressure, ensured that the minimum amount of cooling water was used to condense the overhead product to its bubble point. Changes permitted the shutdown of a 150 kW cooling water pump and a 50 kW cooling water fan, resulting in annual savings worth £40,000.

Case Study 1 (Section 8.1) further demonstrates the savings from avoiding sub-cooled reflux.

4.3.5 *Reboiler Control*

The reboiler is usually controlled by steam flow. Without automatic flow control, excessive steam flow to the reboiler can result, leading to an over-purified product.

The reboiler vaporises liquid in the column, increasing pressure unless the condenser provides reflux to quench the vapour. Pressure is therefore generated in the reboiler, but is controlled by providing reflux in the condenser. Energy savings will result if a lower pressure steam can be used in the reboiler. This could be achieved in one of the following ways:

- *examining current operating conditions*

  Steam pressure in the reboiler may already be sufficiently low to allow lower pressure steam to be used, particularly where the reboiler is oversized.

- *reducing the column pressure providing there is sufficient capacity in the condenser*

  The extent to which pressure can be reduced is determined by the spare capacity in the condenser. Reducing pressure also increases the relative volatilities making the separation easier, and reduces reflux ratio, saving more energy. The colder ambient temperatures in winter allow for colder process temperatures in condensers.

Reported case studies show that winter-period distillation column energy can be reduced by up to 25% through application of floating pressure operation.

- *using tube inserts*

  These enhance heat transfer and reduce the required temperature in the reboiler. This results in reduced steam pressure requirements.

- *using standby reboilers in parallel*

  These reboilers increase the heat transfer area and allow use of a lower pressure steam. Even heavy fouling columns, which need standby reboiler facilities, can be scheduled to utilise lower pressure steam providing the pipework for the higher pressure steam is maintained.

- *using a thermocompressor to generate an intermediate pressure level where the steam pressure in a reboiler is lower than its supply pressure, but not sufficiently low to allow the use of site low pressure steam*

  A thermocompressor will use a proportion of high pressure steam to compress the lower pressure steam to the required intermediate level. This approach provides reasonable flexibility to accommodate pressure changes, as the high pressure steam is always piped up to the motive side.

- *providing additional surface area in cases where the temperature on the process side of a reboiler is sufficiently low, but the steam pressure is close to the supply pressure*

  Additional surface area can be provided by a new tube bundle with extended surface (twisted tube), a new parallel reboiler or a replacement reboiler.

Installation of a thermocompressor provides low-cost route to savings

A column using 15 tonnes/hour of medium pressure (MP) steam in a reboiler operates with a bottom product temperature sufficiently low to use low pressure (LP) steam. Due to the fouling nature of the bottom product, two reboilers are installed with the standby being used while the on-line reboiler is cleaned. Using both reboilers in parallel reduces the steam side pressure requirement. The steam pressure in the on-line reboiler is just above the LP pressure, but increases due to fouling during a 12-month period to a pressure equivalent to the MP level. Once the pressure reaches the MP level the exchanger is taken off-line for cleaning. After cleaning LP steam alone was sufficient, but MP steam was required after three months' operation.

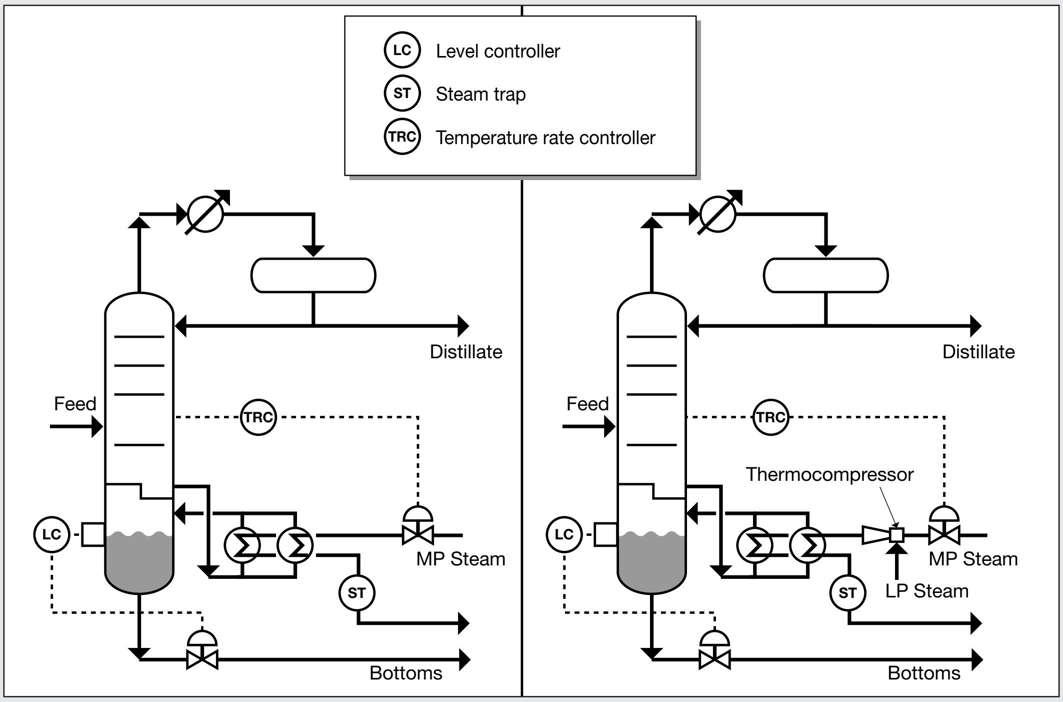


Fig 9a Column with spare reboiler

Fig 9b Column with thermocompressor

Installing a thermocompressor allowed the use of LP for the first three months, followed by a combination of LP and MP until the next scheduled cleaning. On average this shifted 10 tonnes/hour of MP on to LP and saved £200,000/year for the nominal investment of £10,000.

4.3.6 *Insulation*

Insulation reduces heat losses and thereby reduces the load on reboilers and condensers. Heat losses in condensers are particularly important in low temperature distillation, where refrigeration is used. Refurbishing insulation on an existing distillation column should be considered in any efficiency project because:

- poorly maintained or badly-fitted lagging is inefficient;
- changes in column operating pressure and/or temperature may mean that a different insulation thickness is needed compared with that for the original design;
- changes in energy and/or insulation costs may make it economic to increase insulation thickness.

4.3.7 *Fouling*

Fouling in a reboiler increases the required steam pressure. After prolonged fouling, the pressure may rise to be in excess of the supply pressure. At this point, if there is no higher pressure steam available, the throughput of the column will be reduced or the reboiler must be taken off-line for cleaning. Monitoring plant performance will show when fouling is starting to affect plant performance, allowing action to be taken. Computer-based monitoring can assist in detecting fouling and optimise cleaning schedules. There are also several modifications which can help to reduce the effects of fouling, including:

- installing a spare reboiler to allow frequent on-line cleaning;
- using tube inserts to reduce tube wall temperatures and increase tube wall shear forces;
- injecting steam or inerts into the reboiler to reduce the boiling point (most fouling mechanisms tend to increase at higher temperatures);
- chemical dosing;
- changing from natural thermosyphon to forced circulation reboiler;
- installing more surface area within the reboiler reducing the required ΔT (a design change).

4.3.8 *Condensate Recovery and Steam Trap Maintenance*

These are common issues for any heating duty and should be considered when trying to reduce the energy requirements of distillation.

Condensate recovery should be in place on most existing installations. Converting columns with direct steam injection to use a reboiler will reduce both energy and demineralised water usage, as condensate can be returned hot to the boiler house to replace cold make-up water.

Steam traps should be properly maintained to avoid leaks and passing.

Replacing steam trap cuts reboiler duty

A reboiler, originally designed to use MP steam, was using high pressure (HP) steam due to unsatisfactory operation at the lower pressure. Detailed investigation showed that the steam trap was passing, resulting in the reboiler duty being provided by superheat only and an excessive steam flowrate. Replacing the steam trap enabled MP steam to be used, at a much reduced flowrate.

5. CONVENTIONAL REVAMPS

Whenever a revamp is planned, separation energy should be considered. Heat integration, process control improvements, change of column internals and some thermal redesign initiatives are potentially feasible in such circumstances.

The changes covered in this Section encompass opportunities which require some investment to realise, but no advanced technology. The main costs will come from the loss of production while the equipment is installed, but these can be minimised by careful planning, pre-installing as much as possible and completing installation during scheduled shutdowns.

5.1 Heat Integration

Perhaps the largest reductions in distillation energy consumption can be brought about through effective heat integration. The well-established tools of Pinch Technology can be used[3] to ensure that a distillation column is appropriately placed.

Using the grand composite curve

The grand composite curve represents the heating and cooling demands of a process. Above the pinch point, heat must be provided from an external source such as steam; below the pinch, heat must be rejected to an external utility such as cooling water.

The grand composite curve shows the external heat to be added and rejected, as well as the temperature at which this can be done. When considering heat integration of a distillation column with the background process, the dominant heating and cooling duties associated with the column are the reboiler and condenser duties. The thermal profile of the distillation column is shown as a ‘box’, with heat being added at a high temperature in the reboiler to be rejected in the condenser at a lower temperature.

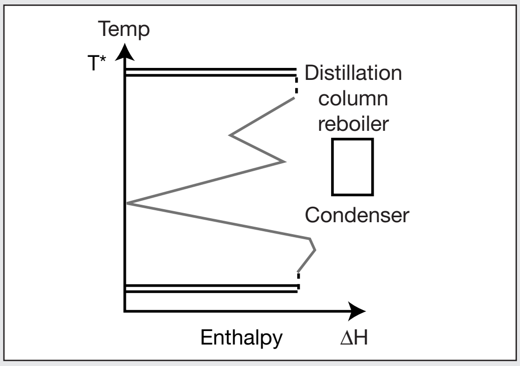


Fig 10 The process grand composite curve

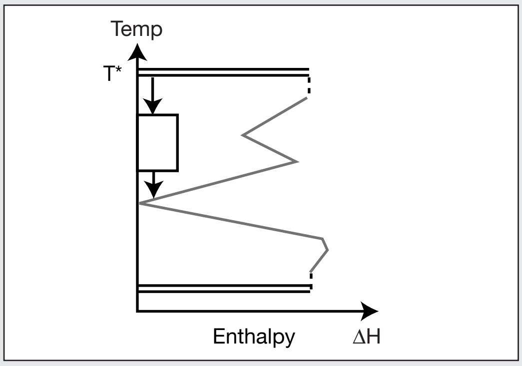


Fig 11 An appropriately-placed distillation column

If the column is integrated with the reboiler and condenser temperatures on opposite sides of the pinch then there can be no energy saving by integration. Integration must be done under conditions in which the reboiler and condenser are both above or both below the pinch. This is known as the appropriate placement of distillation columns.

If a distillation column is inappropriately placed for heat integration, the first strategy is to change the column pressure such that the reboiler and condenser temperatures are both on the same side of the pinch.

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[3] Further information on Pinch Technology can be found in Good Practice Guide 242, *Process Integration*, and in Linnhoff B, *Pinch Analysis*, Chemical Engineering Progress, 90(8), pages 33 - 57 (Aug 1994).

If a distillation column can be appropriately integrated with the background process, it can effectively be run at no energy cost.

Any heat integration project should be accompanied by a control design review. Any problems can easily be overcome by using modern control techniques.

5.2 Feed Locating/Conditioning

An initial assessment of feed conditioning issues is given in Section 4.3.2. During a revamp, additional techniques for optimising feed location and conditioning can be applied.

Preparation of a column grand composite curve or column profile is the ideal starting point for optimising feed location and condition. A column profile shows the heating or cooling requirement of the separation *for each stage*. The data used to generate the curves are taken from a converged simulation of the column.

Column profiles are typically used:

- as an aid to the correct placement of feeds;
- to identify the potential benefits of feed pre-treatment;
- to determine the scope for side reboilers and condensers and their best location.

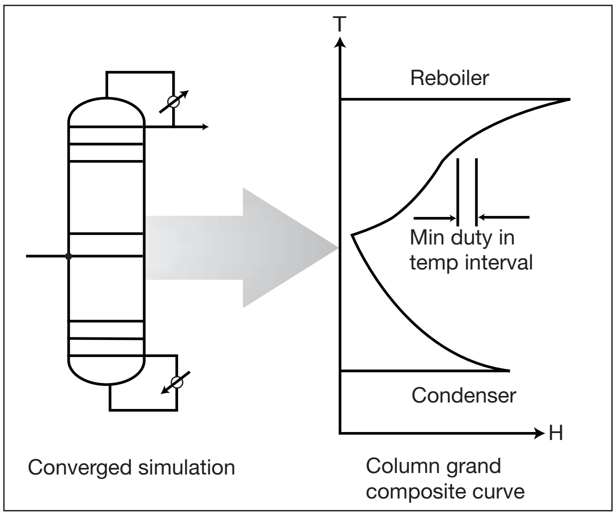


Fig 12 Generation of a column profile

Column profiles combined with hydraulic data provide a very effective aid to removing bottlenecks.

Using a column profile to correct feed location

A column with a feed on stage 13 was simulated, and the data used to generate a column profile (solid line in Fig 13). The profile showed a large spike associated with the feed stage, indicating that the feed should be moved down the column.

The column profile after the modification (dotted line in Fig 13) shows a displacement on the enthalpy axis, indicating savings in the reboiler and condenser duties.

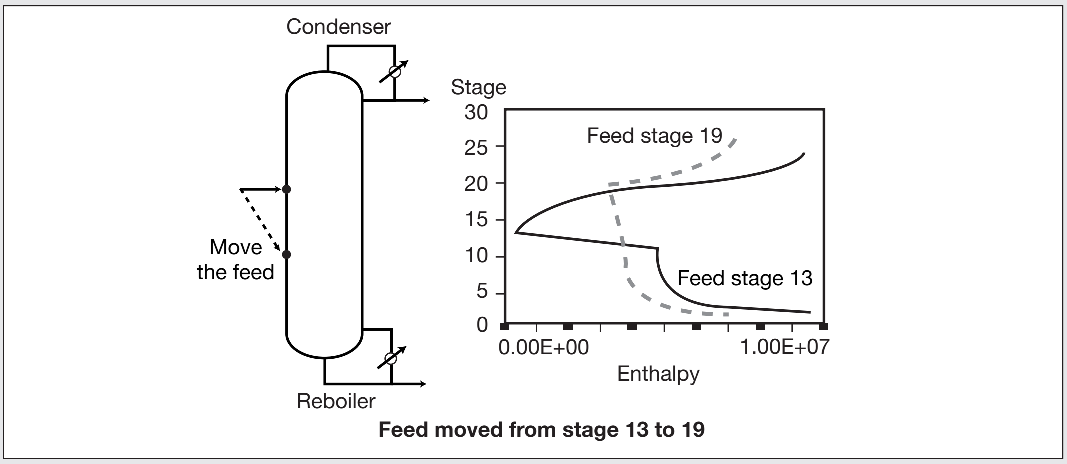


Fig 13 Relocated feed reduces energy requirement

For a properly specified distillation column it is usual to include several feed locations (to allow for changes in feedstocks, etc), making the relocation of feed a low-cost option with good returns. Adding a new feed nozzle is expensive, especially if a specific shutdown is required, and in these cases it may be worth adding internal distributors (piping) to relocate the feed point.

With the correct feed location, a column profile can then be used to determine the potential benefits of feed heating or cooling.

Using a column profile to assess benefits of feed heating

The column profiles in Fig 14 show the reduction in reboiler duty that can be achieved by feed heating and the temperature at which the heat must be supplied. Energy and cost savings will result if the heat can be provided by a cheaper utility or, ideally, recovered process heat.

Note that there is not a 1:1 relationship between feed heating and reboiler savings, because the additional heat input will increase condenser duty.

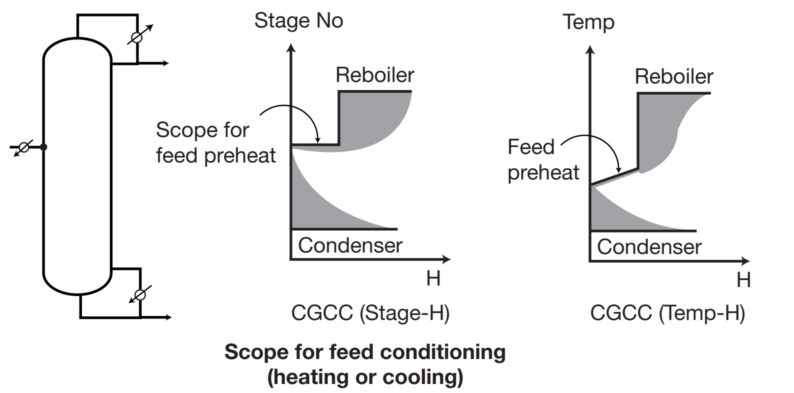


Fig 14 Assessing the benefits of feed conditioning

Scope for cooling the feed can also be assessed using a column profile. Feed cooling is an issue where the column condenser is operated using refrigeration. The condenser duty can be reduced by precooling the feed using an inexpensive utility (such as cooling water) or by process cold recovery.

When implementing feed conditioning modifications:

- Consider in detail the hydraulic conditions at the feed point.
- Check that the design of the distributor is suitable if phase changes occur.
- Consider the changed vapour/liquid loadings in the column around the feed.
- Take into account the phase of the feed in the preheater: if the preheater is to be operated without a change of phase, a large heating duty indicated by the profile would have to be accommodated by sensible heating only. This may result in an excessive temperature rise.

Feed/bottom product recovery exchangers are often found on plants. While these exchangers are conveniently located, they are not necessarily the best use of available heat. For example, a feed/bottom product recovery exchanger on a column may reduce the reboiler LP steam duty but increase the feed heating duty on a downstream furnace, resulting in an overall increase in costs.

Make sure that any existing feed/bottom product recovery exchanger is correctly sized. Oversized exchangers provide no further reduction in the reboiler duty, and can actually increase the condenser duty as well as the heating duty on a downstream operation. In these cases, use a manual by-pass to optimise recovery at low cost.

5.3 Side Reboilers, Side Condensers and Pumparounds

Heat can be added at intermediate points in the column, with some of the required heat added at a lower temperature in a side or inter-reboiler and some of the heat rejected at a higher temperature in a side or inter-condenser. The benefits of these side components include:

- a lower temperature heat addition which may allow a cheaper source of hot utility to be used, such as low pressure steam in the inter-reboiler in place of high pressure steam in the bottom product reboiler;
- a higher temperature heat rejection which may allow a cheaper cold utility to be used, such as cooling water in the inter-condenser in place of some refrigeration duty in the overhead condenser;
- the less extreme temperatures at which heat can be added or rejected improve opportunities for heat integration.

Side reboilers and condensers should only be considered after feed preheat has been optimised.

Using a column profile to identify scope for heat addition or removal

Generating a column profile identifies the target for side condensing and side reboiling. The changed vapour/liquid loadings in the modified section(s) must be taken into account when generating the profile.

Projects to install side reboilers or condensers rarely provide a suitable payback as a retrofit on existing distillation equipment, although they may prove cost-effective in capacity debottlenecking.

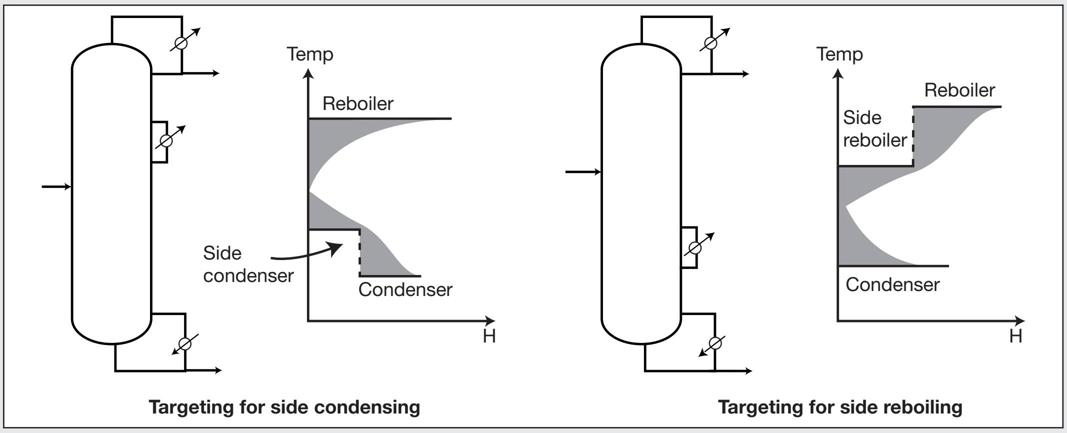
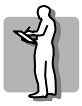


Fig 15 Side condensing and reboiling



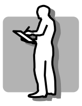
Side condensers are not always practical in retrofit situations. A more conventional way of recovering intermediate heat from a column is by pumparound. A pumparound has the function of an intermediate condenser. Liquid is withdrawn from the column, cooled in a heat transfer section and then returned above the draw (as opposed to a pumpback reflux, which enters below the draw). A typical pumparound application is on refinery fractionation columns which have wide boiling range products.

5.4 Heat Exchanger Design

Most heat exchanger problems stem from the overdesign/safety factors in the system.

Feed/bottom product recovery exchangers are often restricted to a single shell to minimise capital costs. No matter how large such a shell is, it will not be totally effective if there is a temperature cross. In such cases, it may prove more effective to use an exchanger with a smaller surface area and multiple shells.

Reboiler overdesign can result in excess surface area. In steam-driven reboilers, the resulting operating duty may require very low chest pressures, giving condensate handling problems. This leads to operating at too high a pressure, over-reboiling, product giveaway and extra cost. Excess area can be overcome by installing a condensate drum and level control, to enable partial flooding of the bundle.



Air-cooled overhead condensers can be set up so that half of the fans are on variable pitch control, with the other half on on/off switches. With this set-up, half of the fans can be switched out of service for much of the year, saving power and avoiding sub-cooled reflux (see Section 4.3.4). This is good housekeeping practice. If there are no switches, it is worth investigating the cost of addition (see also Section 5.6 on control systems).

5.5 High Efficiency Trays and Packing

High performance trays do not increase separation efficiency as such. The 'efficiency' refers to high *volumetric* efficiencies. The trays are primarily retrofitted to remove bottlenecks. They have improved downcomer designs which allow higher liquid loadings, and improve the separation between dense vapour and liquid in medium- to high-pressure systems.

The improved liquid handling means that the trays can operate with reduced tray spacing. Inserting extra trays into the column increases the number of theoretical stages and hence reduces the required reflux ratio.

High performance packings also have high volumetric efficiencies, enabling a trade-off between higher capacities from an existing column shell and more equivalent stages from a fixed height packing. High performance packings are normally structured packings with a higher surface area to volume ratio than random packings.

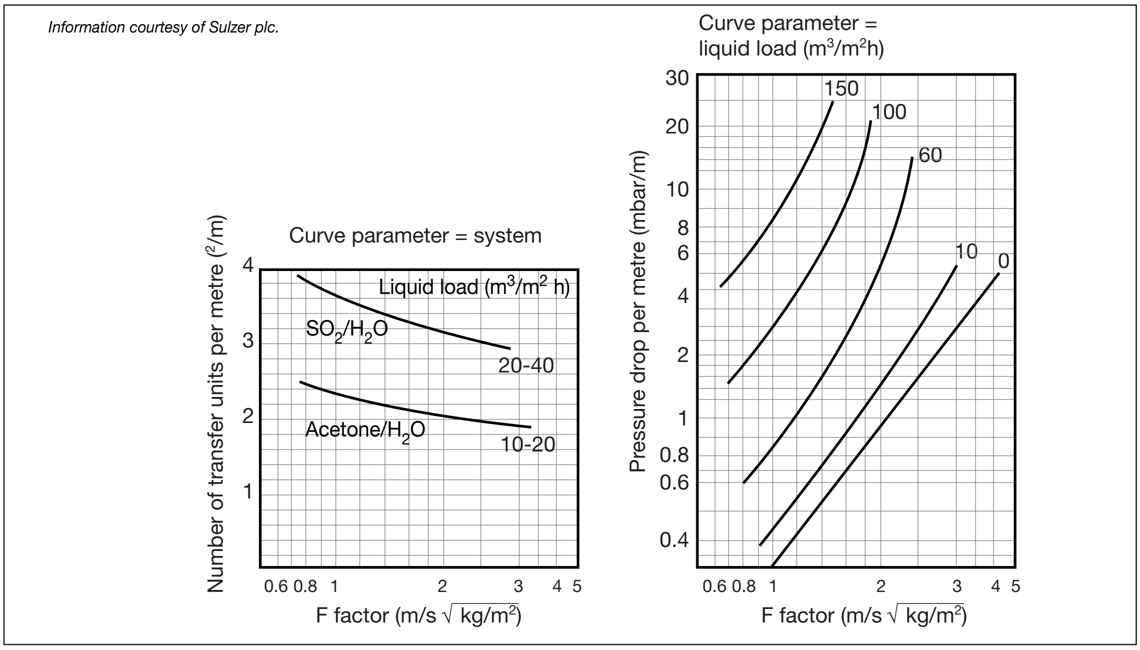


Fig 16 Efficiency curves for trays and packing

5.6 Control Systems

Control systems are critical in terms of improving the energy efficiency of a distillation operation. The systems are low-cost compared with changes to process equipment and provide cost-effective means of improving operating efficiency, often with payback times of a few months. There are some basic aspects to control of distillation columns:

- Controlling the column so that one or more of the products is controlled at the maximum impurity level as limited by product specifications.
- Controlling/optimising feed condition.
- Minimising excess oxygen on fired reboilers and feed heaters.
- Controlling/optimising heat addition and removal where there are multiple reboilers or pumparounds.
- Operating the column at minimum operating pressure.

Significant improvements in these areas can be achieved with relative ease and at low cost as follows.

Reducing disturbances
Control is needed because disturbances arise. With a defined control design, the greater the disturbances, the worse the control. It is therefore good practice to try to reduce or eliminate disturbances at their source. Some basic aspects should be addressed:

- All level controllers on upstream equipment should be reviewed. As far as possible, the controllers should be tuned so that disturbances are attenuated by allowing levels to drift from setpoint (‘averaging level control’).
- All controllers on related equipment (eg feed systems, steam systems, hot oil systems) should be reviewed to ensure they are well designed and tuned properly. In some cases more advanced controls may be warranted.
- Automating procedures that are used regularly to minimise disturbances during transitions, batch operations, grade changes etc.

Control approach
The means used to control reflux drum level (ie reflux flow, distillate flow or condenser duty) and column bottom level (ie reboiler duty or bottom product flow) and column pressure and temperature can have a major impact on operability and energy use. This should be reviewed. Relative gain analysis may help.

Controller tuning
All controllers on the distillation column should be tuned for effective closed loop response.

Column temperature and reflux control
It is often possible to control product qualities so that they can be operated at the maximum impurity level, thereby saving energy by controlling a tray temperature and either reflux ratio (to top product or feed) or reboil ratio (to bottom product or feed). The key issue is choosing the right tray temperature - one that is sensitive to product quality over a range of operating conditions.

Where column pressure is allowed to float, the temperature must be compensated for pressure fluctuations.

If possible, reflux should not be subcooled excessively. Fan switching can help this. Where subcooling is unavoidable it may be helpful to compensate reflux flows for changes in the degree of subcooling so that column internal reflux ratios are maintained.

Feed preheat
Overheating the feed may result in higher condenser duties and pressure control problems. In such cases, controlling the outlet temperature of the feed heater will off load the condenser, which reduces energy costs when the condenser uses refrigerant.

Column pressure
Often column pressure setpoints are set for worst case conditions. Reducing column pressure will often reduce energy costs by making separation easier.

In many cases column pressure can be allowed to float at its minimum value providing column temperatures are compensated for pressure variations.

Level control
Often levels should be tuned for averaging control. This may not be the case when the reboiler or condenser are flooded or there is a very major hazard associated with very high or low level.

Heater excess oxygen control
Where the fired heaters are used (eg feed preheat, reboil or hot oil circuits) automatic control that minimises excess oxygen should be considered subject to the usual safety considerations.

Quality control
In some cases there is sufficient justification to install on-line analysers for use in control or for operator indication. It is important to ensure that maintenance resources are available to keep the analyser working well. It is important to note that it may be possible to estimate qualities from temperatures and pressures in the column, and this may avoid the cost of installing analysers.

Where analysers are installed the additional cost of using them in closed loop is usually small, particularly if a digital control system is installed.

Control of side reboilers, pumparounds, side streams etc
Where the distillation column configuration is more complex, it is often possible to achieve adequate control using simple ratios - eg keep sidedraw flow in ratio to feedrate, keep pumparound duty in ratio to total heat removal.

Advanced control
Many distillation columns are suited to advanced control. Key operating characteristics to look for include:

- High energy cost (eg high purity separation).
- High value of additional feedrate and production is limited by the distillation column (eg maximum reboiler duty, maximum pressure, hydraulic limits, flooding).
- Large difference in product values.
- High value for improving product consistency.

Further information is given in Section 6.9.

5.7 Extractive Distillation

There are more opportunities for optimisation with extractive distillation systems than with conventional systems. As well as pressure, feed condition and reflux ratio, the solvent parameters may be varied. Reducing the solvent flowrate generally saves energy on both the extraction and the stripping columns. It does, however, result in a loss in separation and recovery of both products, but will be acceptable if the products are still within specification. Evaluate the savings against any losses before carrying out any changes.

5.8 Azeotropic Distillation

For azeotropic distillation, the major energy-dependent issue is the choice of entrainer. A more effective entrainer will reduce the energy demands of the system, but you are unlikely to find a more effective entrainer for an existing system.

Energy savings are also possible through improving the separation in the overhead drum. Careful set-up and control of the levels is vital. The phase separation zone for the two liquids benefits from the greatest height that can be arranged to give the greatest flow path and residence time. By resetting the level controls (using upsurge volume if necessary), a better separation may be achieved at minimum cost.

5.9 Vacuum Systems

Vacuum distillation is usually performed because the products are unstable at the boiling point temperatures at higher pressures. Vacuum generation is expensive in terms of energy use, with major increases in cost (capital as well as operating) as the vacuum becomes ‘harder’.

Steam jet ejectors used to create a partial vacuum are susceptible to erosion on the tips of the jets, resulting from wet steam. Any erosion will degrade the performance of the ejector, which will then have to use more motive steam to attain the required vacuum. Jet replacement is a relatively minor project and should be investigated before every shutdown. Examination of steam use records, if they are available, will show whether any action is necessary.

Replacing one or more of the jets with vacuum/liquid ring pumps is a further possibility. These pumps have a high efficiency compared with that of a steam jet ejector and can therefore be cheaper to run. They are also easier to control by the drives. Usually the pumps are used to achieve a harder vacuum than ejectors and data analysis will be needed to determine whether running with a harder vacuum will prove cost-effective.

6. ADVANCED TECHNIQUES FOR DISTILLATION IMPROVEMENT

This Section covers advanced techniques which are more applicable to new equipment design or large-scale revamps. Energy efficiency is an important consideration in any new design, with additional capital costs usually justified on the energy savings during the life of the equipment. While large-scale revamps to reduce energy consumption alone are not normally justifiable, if a revamp is planned for other reasons, separation energy should always be considered.

6.1 Double Effect Distillation

Fig 17 shows the classical double effect distillation arrangement. The feed is split and fed to two separate parallel columns operating at different pressures, making heat integration possible between the condenser of the high pressure column and the reboiler of the low pressure column.

This arrangement can approximately halve energy consumption, but increases capital costs considerably due to the additional distillation shell and heat exchanger.

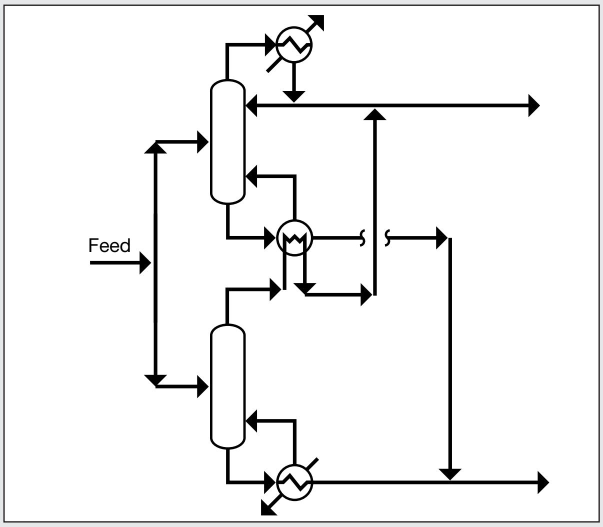


Fig 17 Classical double effect distillation arrangement

6.2 Heat Pumping

Vapour recompression using a heat pump can prove an economic way to save energy costs in the distillation of close boiling mixtures. In other cases, the compression costs and additional capital costs outweigh the savings in heat energy. Successful applications have been reported for the separation of propylene-propane mixtures.

The basic technique is shown in Fig 18. The overhead vapour from the column is compressed and then condensed in the reboiler. Compression elevates the overhead vapour condensing temperature sufficiently to provide the temperature difference needed to drive the reboiler. The condensed overhead vapour is collected in a reflux drum and pressure controlled (with no reflux pump required) to reflux the column.

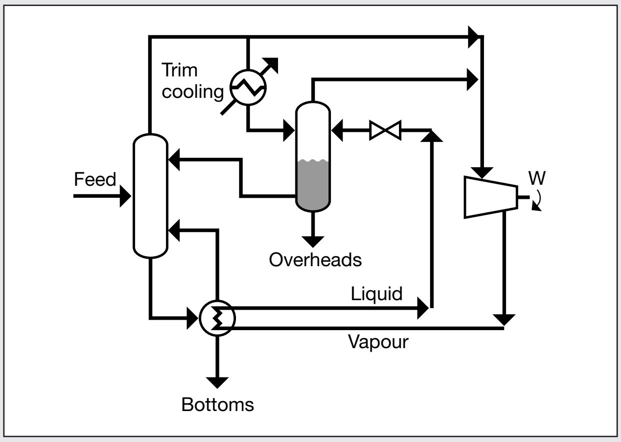


Fig 18 Vapour recompression using a heat pump

6.3 Distillation Sequencing

Separation of a multicomponent mixture into its constituent components requires several distillation steps. The order in which the components are separated influences the capital and operating costs of the system.

For example, a mixture consisting of three components to be separated into pure products has two alternative sequences.

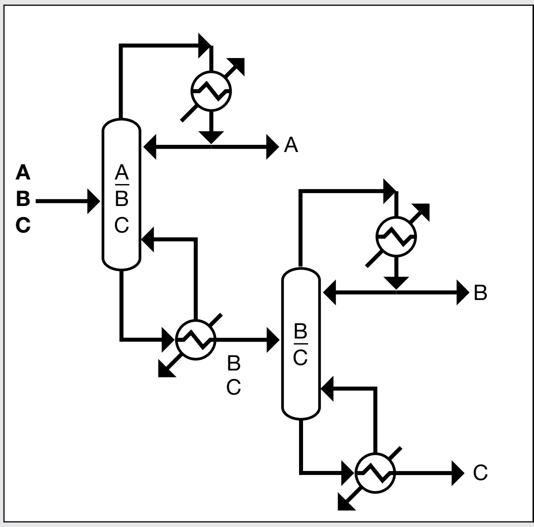


Fig 19a Direct sequence distillation

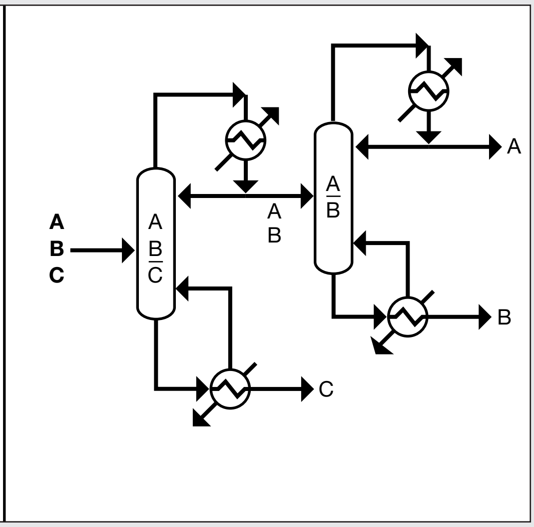


Fig 19b Indirect sequencing distillation

In the sequence shown in Fig 19a, the lightest component is taken overhead as the first product: this is known as the direct sequence. In Fig 19b, the heaviest component is removed first as bottom product: this is known as the indirect sequence. There may be significant differences in energy requirement between the two sequences.

The number of possible sequences increases factorially with the number of components, such that selecting the optimal arrangement rapidly becomes formidable. For example, a five-component mixture has 14 possible sequences, with the energy consumption of the best and worst sequences often differing by about 30%.

Perhaps the most common method for selecting a distillation sequence is the application of empirical rules derived from experience. The following ranked heuristic rules are suggested for illustration.

1 Favour distillation as a separation method.
2 If refrigeration is required, consider cheaper alternatives such as absorption.
3 For sharp separations favour the smallest product set.
4 Remove hazardous or corrosive components first.
5 Perform difficult separations last.
6 Remove the most plentiful component first (provided its relative volatility is reasonable).
7 Favour equimolar splits (provided relative volatility is reasonable).

Despite considerable research, heuristic rules are sometimes fallible and contradictory. Those given here are intended to provide guidelines only and do not guarantee optimality or an approach to optimality of the distillation sequence.

6.4 Sharp versus Distributed Separation

A sharp separation is defined as one where each component appears almost completely in one, and only one, product. In distributed separations, one or more adjacently boiling components in the feed simultaneously appear in two or more products.

Consider a five-component mixture which is split into its components in seven distillation steps using three distributed and four sharp separations (Fig 20). The same separation could potentially be achieved using only four sharp separations. In general, distributed separation sequences require more separation steps than sharp sequences, but can require significantly less energy. The optimal arrangement is therefore a compromise between capital investment and utility consumption.

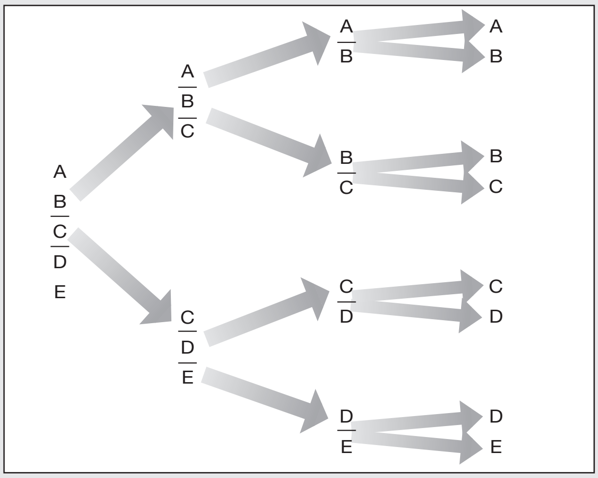


Fig 20 Steps involved in splitting a five-component mixture

6.5 Dephlegmators

A dephlegmator is a refluxed heat exchanger that separates vapour phase mixtures by partial condensation. A dephlegmator can be a conventional (vertical) shell and tube or plate-fin heat exchanger.

Dephlegmators are generally used in cryogenic gas separation applications where refrigeration costs are a significant economic factor. In these applications, incorporating dephlegmators has been shown to give higher recoveries at lower refrigerant loads than conventional cryogenic processing. As a result, dephlegmators are increasingly being used for: processing natural gas, refinery and petrochemical off-gas; air separation; hydrogen recovery; methane separation; ethylene recovery; NGL and LPG processing; and carbon dioxide purification.

Dephlegmators in conventional distillation processes can produce energy savings and greater toleration of variations in composition and flowrate. As well as reducing capital and energy costs, dephlegmators can also improve overall product recoveries.

Dephlegmators can also be applied in a distillation sequence to feed a vapour phase product from one column to the next (Fig 21), resulting in energy savings.

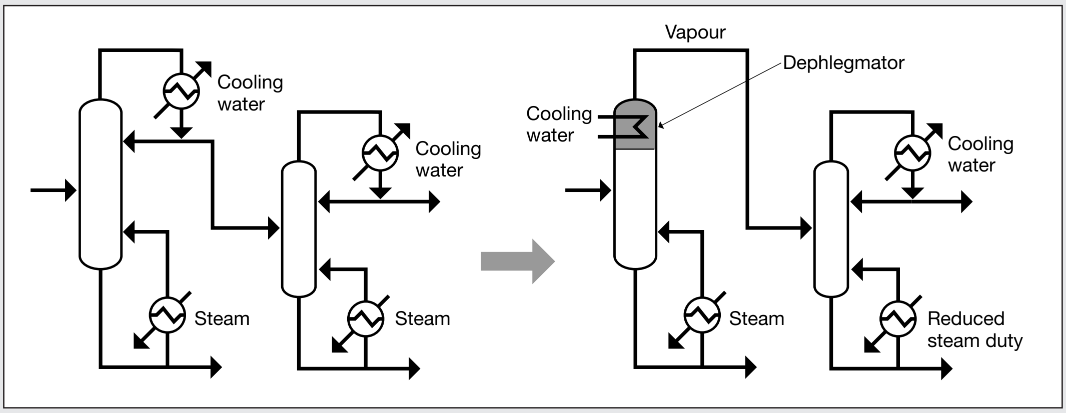


Fig 21 Using a dephlegmator to feed a vapour phase product

6.6 Prefractionators

Prefractionators are one of the most effective ways of reducing energy consumption in distillation. They are thermodynamically more efficient than equivalent conventional two-column arrangements, typically requiring 30% less energy.

An alternative flowsheet for separating a three-component mixture using a prefractionator is shown in Fig 22.

The first column of the prefractionator separates A from C. The separation of B from the AB and BC mixtures coming from the prefractionator is carried out in the main column.

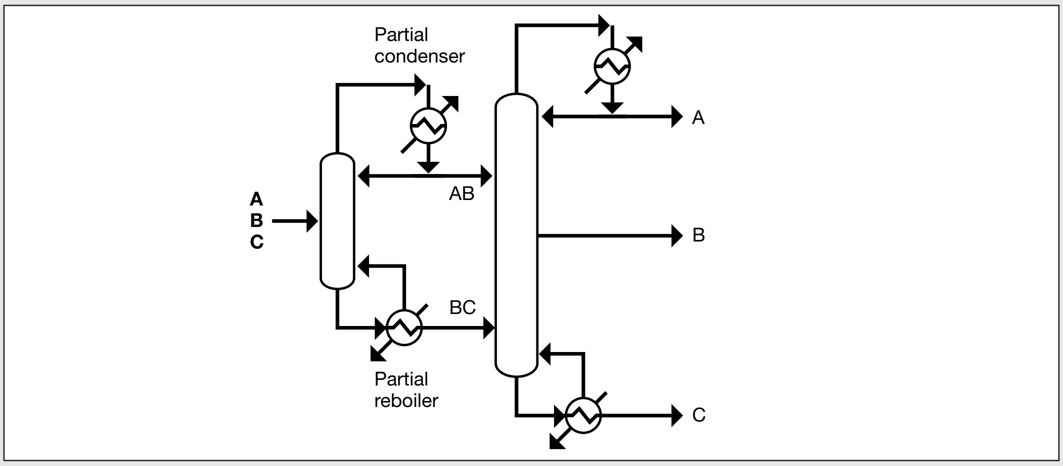


Fig 22 Separation of a three-component mixture using a prefractionator

6.7 Thermal Coupling

Rather than have a system of two columns each with its own reboiler and condenser, it is possible to couple two columns thermally. Material flows then provide some of the heat transfer by direct contact, saving investment in heat exchange equipment.

The direct sequence (Fig 23a) has been thermally-coupled by transferring liquid from the bottom of the first column to the second. The vapour required by the first column is now supplied by the second column, instead of by a reboiler. The four column sections marked 1 - 4 can alternatively be rearranged to form a side rectifier, as shown in Fig 23b.

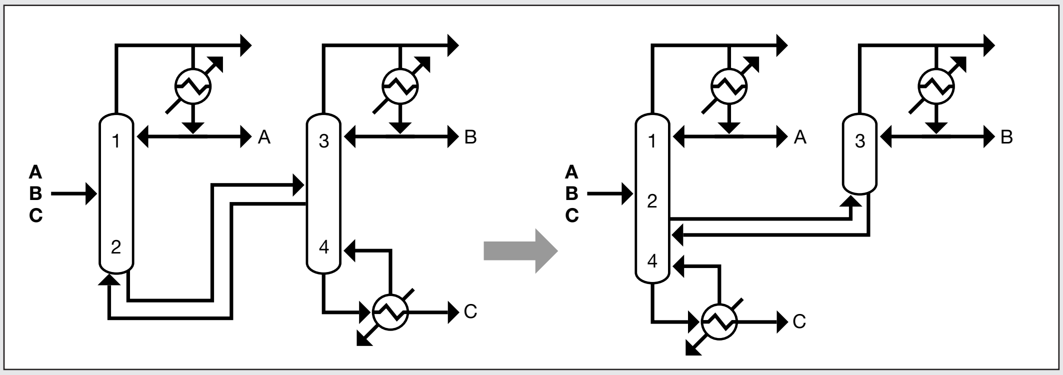


Fig 23a Thermally-coupled direct sequence

Fig 23b Side rectifier arrangement

In a thermally-coupled indirect sequence (Fig 24a), the condenser of the first column is replaced by liquid from the second. In this case, the four column sections can be re-arranged to form a side stripper.

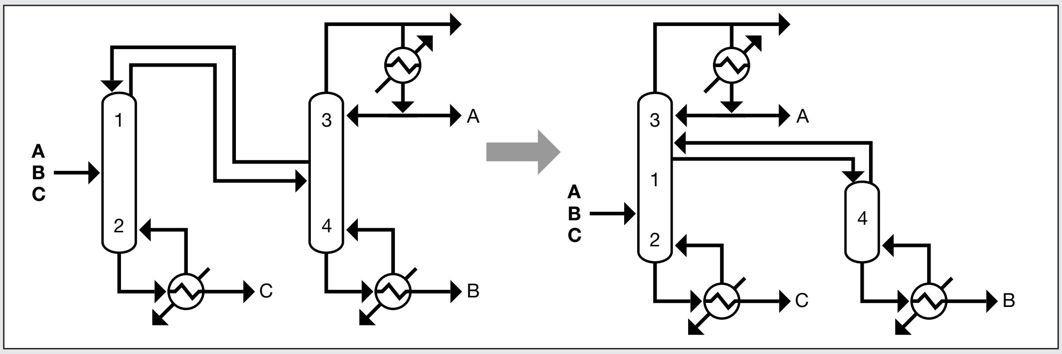


Fig 24a Thermally-coupled indirect sequence

Fig 24b Side stripper arrangement

The side rectifier and side stripper arrangements both reduce energy consumption by up to 20% compared with conventional two-column arrangements.

6.8 Divided Wall Columns

Divided wall columns are a special case combining the benefits of prefractionators and thermal coupling.

The prefractionator arrangement (Fig 25a) and the thermally-coupled columns (Fig 25b) are equivalent in terms of total heating and cooling duties, although there are differences in the temperatures at which the heat is supplied. Both require less energy than side rectifier and side stripper configurations for the same separation.

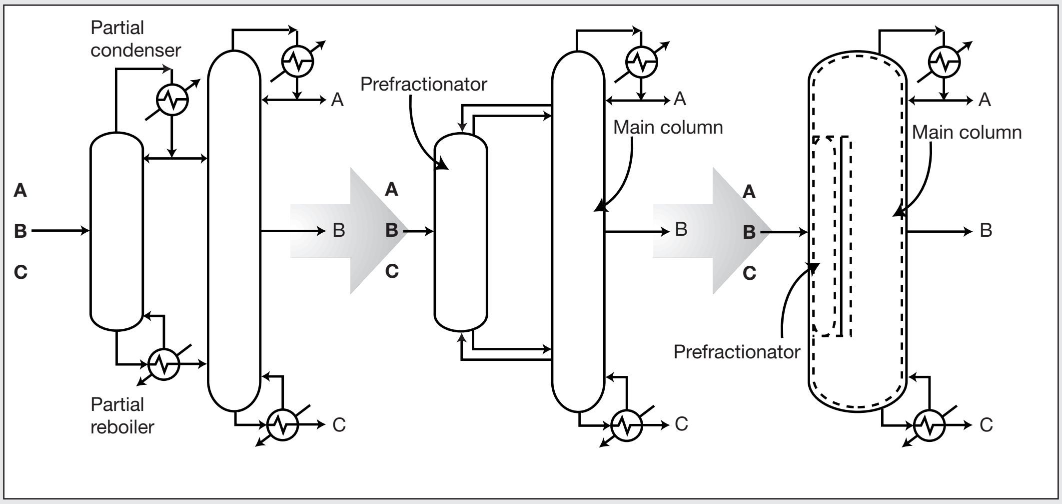


Fig 25a Prefractionator arrangement

Fig 25b Thermally-coupled columns

Fig 25c Dividing wall column

The arrangement in Fig 25b can also be realised in a single distillation shell, called a Petlyuk column, with a vertical baffle dividing the central section of the column into two parts, as shown in Fig 25c. In addition to the 30% energy saving compared with a conventional sequence, the dividing wall column typically incurs 30% lower capital costs than a two-column arrangement.

Until recently the dividing wall column had not been used in practice. One major company has announced that it has commissioned twelve such columns. A consortium of companies (BP, Exxon, Glitsch, MW Kellogg, ICI and Shell) together with the Energy Efficiency Best Practice Programme recently sponsored research into dividing wall columns at UMIST. The research, based on pilot plant studies, concluded that the column is no more difficult to operate than a conventional column.[4] In addition, control can be achieved using standard techniques.[5]

Some of these more advanced techniques can lead to a process that is much harder to control because of:

- interaction;
- strange dynamic behaviour;
- slower process responses.

Any site considering these types of more sophisticated process arrangements should review the controls needed to make the column operable.

6.9 Advanced Control and On-line Optimisation

Most distillation columns are built with a basic level of process control to:

- regulate the material balance by controlling column levels;
- regulate the energy balance by controlling tray temperature and pressure.

As outlined in Section 5.6, there are many simple control improvements that can be achieved that will help with the performance of a distillation column.

Increasing levels of sophistication are possible in control of a distillation column as follows.

Advanced regulatory control
Multi-level cascades can be applied in a distillation column so that:

- reboiler flows are adjusted to reflect changes in reboil medium and maintain a constant reboil duty;
- pumparound operation is adjusted to maintain constant pumparound duty;
- reflux flow is compensated to allow for variation of subcool;
- reboil and reflux flows/duties are adjusted by feedforward schemes to allow for changes in feedrate;
- tray temperatures are cascaded to reboil or reflux feedforward schemes to maintain constant column temperatures;
- pressure is allowed to float and tray temperature controllers are compensated to allow for pressure or partial pressure fluctuations;
- tray temperatures or reflux/reboil ratios are trimmed in closed loop by quality controllers. Quality is measured by an analyser and is rigorously validated before use in a controller or quality is inferred (using first principle models, neural net or other statistical models). Usually one-way decoupling and/or model-based control will be used with the quality controllers;
- reboil or reflux flows are overridden to manage constraints (eg % flood).

These types of scheme are easily built in many modern digital control systems and are of value where economics seldom change, good control of some qualities is not essential and effective constraint management is not of great value.

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[4] The results of this research are due to be published in Future Practice Profile 87, available 1999.

[5] For further information see Lestak and Collins, *Advanced Distillation Saves Energy and Capital*, Chemical Engineering, pages 72 - 76 (July 1997).

Multi-variable control and real-time optimisation
Advanced regulatory controls are usually complemented with multi-variable controllers to ensure reliable constraint management and effective quality control. The most successful multi-variable controller technique is model-predictive control, and some digital control systems offer these as options.

Model-predictive controllers (MPCs) use dynamic models of the process that are determined by plant test to calculate control adjustments that:

- hold the process at targets or within limits;
- move the process to the most economic operating point.

MPCs have been widely applied to distillation columns, distillation trains and entire process plants. Methods are available for enhancing these controllers to allow for:

- extreme non-linearity;
- unconstrained operating points.

Other control techniques
A variety of other control techniques is available (eg fuzzy logic). By and large the methods outlined above are well proven and offer the most reliable solution.

Choosing what control to apply
The level of the control to be applied depends on the savings that can be achieved through improved control and the nature of the column. It is usual to determine likely benefits before selecting methods.

It is estimated that 10 - 15% excess energy is used in a broad spectrum of distillation applications. Improved control and optimisation can therefore lead to large energy savings, particularly on high reflux ratio columns, coupled systems that are interactive and systems with large time constants.

Industrial applications of advanced control and optimisation have resulted in:

- significant energy savings;
- improved recovery of high value components;
- increased capacity.
- more consistent quality (higher process capability indices);
- faster grade change;
- more rapid recovery from process upsets.

Profitability improvements from improved control can be as high as 10 - 15%, mainly from capacity and recovery improvements. Payback times are often a few months.

6.10 Computerised Process Monitoring

It is common to find digital control and information systems on process plants and it is often possible to exploit these systems to improve overall production management through improved monitoring.

The following areas are opportunities for improving profitability through monitoring:

- Implementing calculations that indicate incipient problems or deteriorating performance using key performance indicators (eg estimated quality, tray efficiency, energy use per tonne, profit per tonne, % flood).
- Implementing methods of monitoring measurements and calculated values to help operators, engineers and managers to decide when performance is deteriorating (eg univariate and multi-variate SPC, clustering algorithms).
- Implementing methods for isolating the area of the process where the problem or opportunity is occurring (eg patter recognition, expert systems).
- Providing automated guidance (eg expert systems, document management).
- Analysis for long-term improvement (eg data visualisation, data mining, simulation).

7. <u>CHECKLIST</u>

The checklist in this Section provides a quick reminder of the measures covered in detail in the earlier Sections of the Guide.

DETERMINE POTENTIAL FOR SAVINGS

- ☐ Assess current column performance.
  Compare simulation of current operations with operation under design conditions.
- ☐ Use column grand composite curve to identify possible improvements to operation/design, e.g. reduce reboil and reflux, change feed condition.

CONSIDER ENERGY-SAVING TECHNIQUES

Consider low-cost, low technology options first.

- ☐ Are all hot and cold vessels, pipes, heat exchangers, valves, etc, insulated adequately?
  Re-assess insulation needs based on current operating pressure/temperature and energy/insulation costs.
- ☐ For clean duties consider structured packing as an alternative to trays, to reduce column pressure drop.
- ☐ For 'dirty' duties, does fouling restrict column performance?
- ☐ Consider high efficiency trays/structured packing to get increased separation stages.
- ☐ Can you reduce reflux/reboil?
  Use simulation to determine any savings.
- ☐ Review operation of control system.
  Is it over reboiling, etc? Is the product purity unnecessarily high because of poor control/measurement reliability?
- ☐ Check condenser and reboiler operation.
  Remember $Q = U \times A \times \Delta T$, so if ΔT is too high there may be fouling or under-sized heat exchanger.
- ☐ Is there scope for thermal integration of condensing and/or reboiling duties?
- ☐ Is there scope for using lower cost utilities for condensing and/or reboiling duties?
  A marginal change of column operating pressure may facilitate their use.
- ☐ Would additional separation stages allow reduced reboil/reflux?
  Consider high efficiency/low pressure drop internals.

MAKE SURE CHANGES WILL NOT COMPROMISE COLUMN PERFORMANCE

Consider the possible consequences of any changes to operation, for example:

- ☐ Are materials temperature sensitive?
- ☐ Will existing internals cope with changes to hydraulic conditions?

8. GOOD PRACTICE CASE STUDIES

8.1 Case Study 1: Reduced Sub-cooling of Reflux

A company wanted to modify the operation of its column condenser so that:

- steam generation was increased from the column condenser;
- reflux sub-cooling was minimised.

Sub-cooling of reflux does not improve separation performance within the distillation column. Typical reasons for sub-cooling include:

- an oversized condenser;
- net positive suction head (NPSH) requirements of reflux pumps;
- a reduction in light ends venting.

In this column, a vent condenser existed so there was no problem with the loss of light ends, and NPSH was not a problem for the reflux pumps.

The company modified the column pressure control. The existing control system showed that condensed liquid passed through a sub-cooler using cooling water at its maximum rate (Fig 26a). In the proposed system (Fig 26b), the cooling water flow would be controlled via a split range controller. The first controlling range from the pressure controller (PC) would adjust the steam pressure before opening the cooling water valve, increasing the condensing duty in the main condenser. Under normal operation of the revised scheme the subcooler has no duty. In extreme conditions the new split range controller can open up the cooling water supply to the subcooler. As the heat exchanger is suitable for this increased duty, no new major items of equipment would be required.

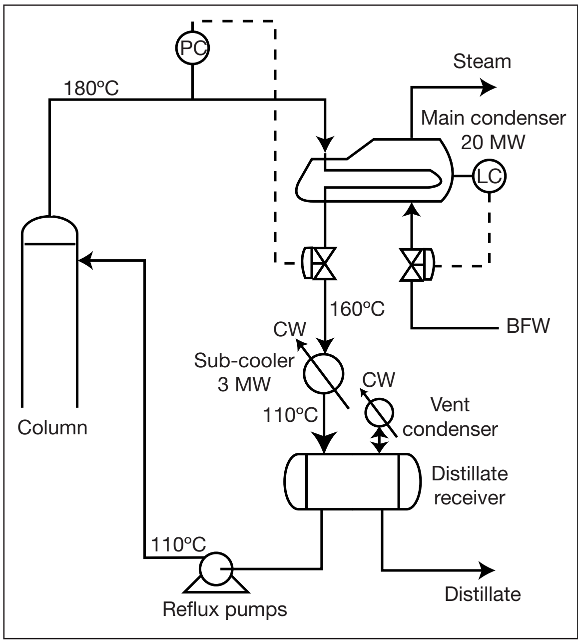

Fig 26a Original control system

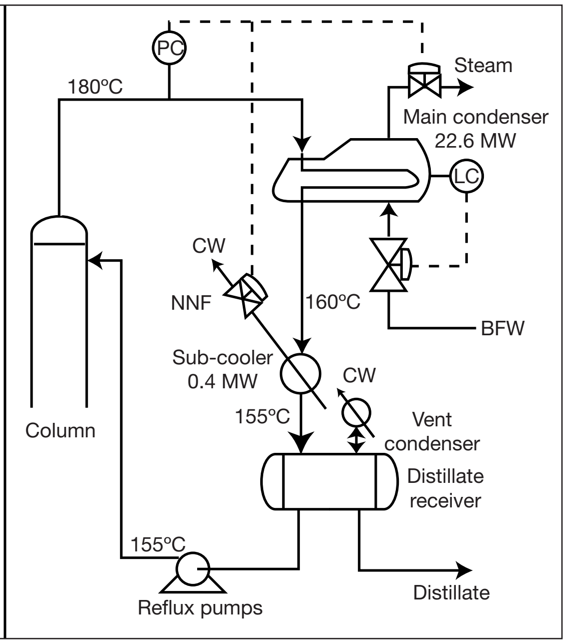

Fig 26b Modified control system

Energy savings due to increased steam generation in the condenser are equivalent to 4 tonnes/hour of steam, worth £200,000 per year. The investment cost is estimated at £30,000, giving a simple payback period of just over 10 weeks.

8.2 Case Study 2: Implementation of Advanced Control System (BP/Mobil)

BP aimed to optimise steam use in the column reboilers.

A refinery dehexaniser was designed to operate with a side reboiler to allow the use of cheaper utilities to provide part of the large column heating duty. The bottom product reboiler operates using high pressure (HP) steam (45 bar) and the side reboiler with medium pressure (MP) steam (10 bar). The column operating costs are thus significantly less than for a column using only HP steam.

Under normal operating conditions, 17 tonnes/hour of HP steam and 20 tonnes/hour of MP steam were required, i.e. 47% of the duty was provided by HP steam.

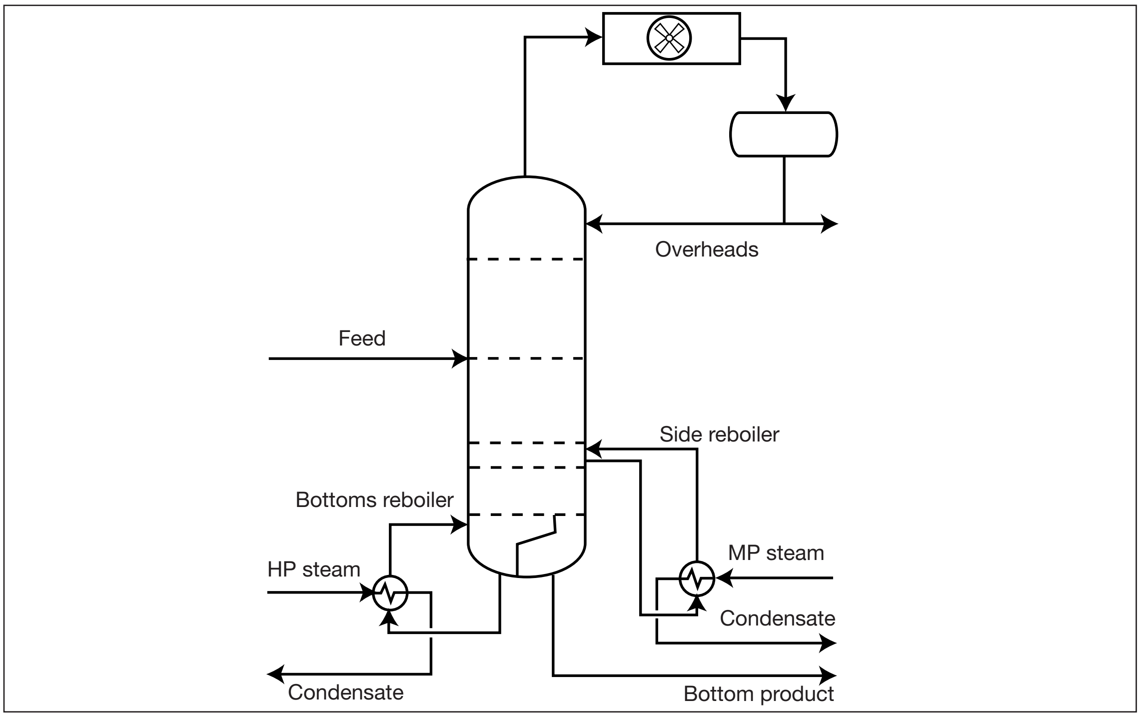

Fig 27 Improvement via control

An advanced control system was implemented to optimise the balance between HP and MP steam use (Fig 27). There was a significant shift towards MP steam use, such that HP steam now provides just 39% of the necessary column heating. In addition, the control system was able to reduce the reflux ratio without affecting product quality, decreasing the overall energy requirement by 26%.

The advanced controls achieved a simple payback period of less than one year.

8.3 Case Study 3: Column Feed Conditioning (EVC)

In 1996, EVC started a rejuvenation project of its Vinyl Chloro Monomer (VCM) facility in Runcorn, Cheshire. As part of the revamp, the hydrogen chloride (HCl) column capacity needed to be increased by 50%. A completely new column, reboiler, condenser and, most importantly, a new mechanical refrigeration set were required. The capital cost of these design changes was estimated at £4,000,000.

EVC planned to reduce capital investment costs by improving distillation efficiency. Proper conditioning of column feeds can often reduce either reflux or reboiler rates without affecting separation. The benefits include:

- reduced condenser or reboiler duties;
- reduced vapour/liquid loading.

In the HCl column, by cooling the feed below the ambient temperature, the vapour/liquid loading, and hence condenser duty, can be reduced to levels allowing the existing refrigeration unit, condenser and top section of the column to be re-used. To achieve this a new, much smaller refrigeration unit is needed on the feed. Although the combined refrigeration duties are similar, the feed refrigeration is at a higher temperature and so has a much better performance coefficient, giving lower operating costs.

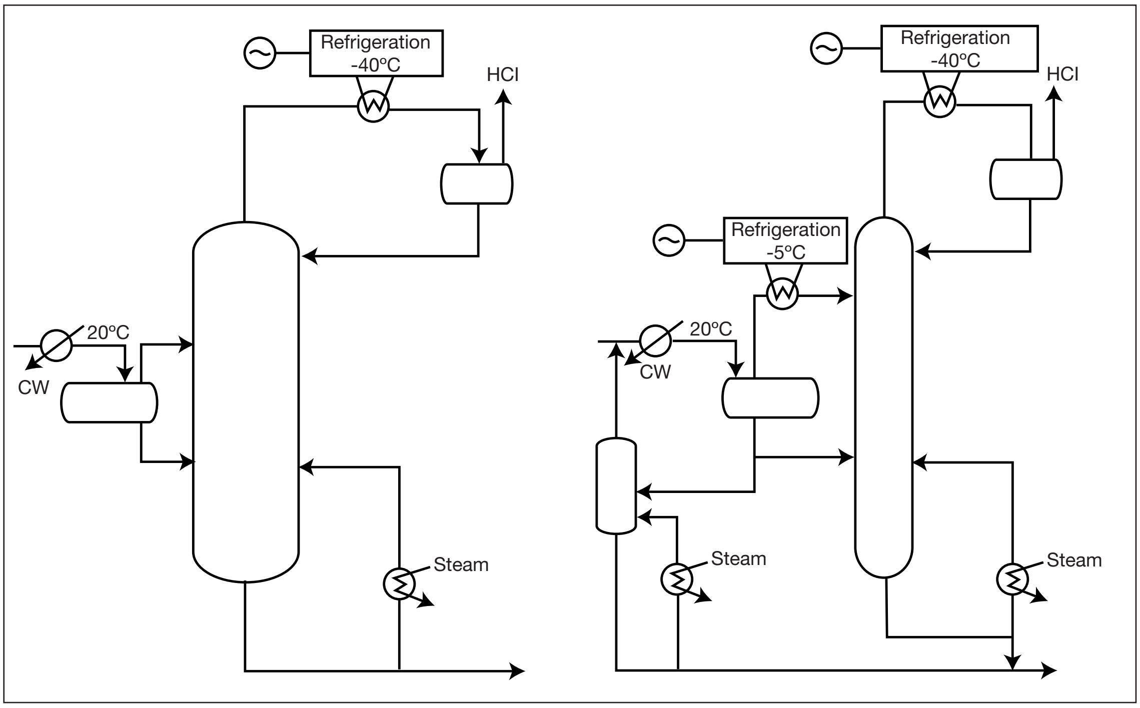

Fig 28a Original design

Fig 28b New design

The new design reduced the capital investment for the revamp to approximately one-quarter of the original costs, saving around £3,000,000. The operating savings were essentially in refrigeration power reduction.

8.4 Case Study 4: Ethylbenzene/Styrene Separation in a Packed Vacuum Column (Chevron Chemical Company)[6]

The original large column at the Chevron Chemical Company contained high-efficiency cross-flow sieve trays, which were subsequently replaced with Norton IMTP random packing. The column now has a rectifying section 9.0 m in diameter, containing one bed of carbon steel IMTP 40 packing, 9.5 m deep. The stripping section is 7.5 m in diameter and contains three beds of carbon steel IMTP 25 packing, each 7.5 m deep. The operating pressure is 50 mm Hg at the top and 190 mm Hg at the bottom. The reflux ratio is 8-10:1.

On start-up, with the new packing installed, the column showed instability as design rates were approached. The pressure drop was higher than expected in the top stripping bed. The number of stages was estimated to be about 40, compared with the 76 stages expected from the vendor's pilot tests. Sight-glasses attached to the liquid distributors showed abnormally high liquid levels.

Chevron therefore began troubleshooting. The column was shut down and opened, and the distributors and support plates were found to be plugged by rust and gasket material. The distributors were modified to provide fewer, larger holes, and the packing and all column internals were cleaned chemically.

[6] Further details can be found in McMullen B D, Ravicz A E and Wei S-Y J, *Trouble Shooting a Packed Vacuum Column - A Success Story*, Chemical Engineering Progress, 87(7), pages 69 - 74 (1991).

The column was started up, but the problems of high pressure drop and a reduced number of stages persisted. It was concluded that insoluble material brought in with the feed had lodged in the packed bed below the feed. The column was hydrocarbon washed, water washed and steam dried. On restart, levels in the distributors had improved, but were still above normal, and the number of stages had now improved to 50.

Using fibre optic methods to view the column operation revealed more fundamental problems, which resulted in the distributors being redesigned. The column was restarted yet again, and the number of stages rose to 63, considerably closer to the expected 76 stages. It was felt that some plugging material still remained in the column.

The experience at Chevron shows that:

- excellent liquid distribution is critical for a successful packed column;
- plugging by debris or corrosion products can ruin even the best distributor;
- carbon steel packing must be protected from rusting when exposed;
- liquid should be remixed between packed beds;
- rust, scale, sediment, etc, must be excluded from entering the column.

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